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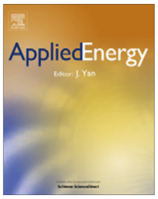

Pelletization of torrefied sawdust and properties of torrefied pellets

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ABSTRACT

Pelletization of torrefied sawdust from a fluidized bed reactor was investigated to quantify the energy consumption and pellet properties, including moisture adsorption, pellet density and Meyer hardness. Energy consumptions in compaction and extrusion for torrefied sawdust were significantly higher than those for untreated sawdust at the same compression temperature, while the moisture uptake rate of pellets decreased with increasing the severity of torrefaction. The densities of torrefied pellets were lower than the control pellet due to the loss of chemically bonded water and low-melting point compounds during torrefaction which act as a binding agent when softened at ~100 °C. The properties of pellets were affected by the removal of most low-melting or – softening point components.

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1. Introduction

Wood pellets have been considered as a high quality biomass feedstock suitable for many industrial and residential applications, including combustion and gasification [1–7]. In the commercial pelletization process, sawdust is forced through the dies by rollers to make the pellets of cylindrical shape. Because of compression and friction between particles and the wall, the temperature of sawdust rises to 70–100 °C, softening the lignin component which then acts as a natural binder. Once exiting the pelletizer, pellets are cooled down, causing the pellets to harden and retain the shape [8]. In general, the bulk density of biomass increased from 40–200 kg m^{-3} to 600–800 kg m^{-3}, while the volumetric energy density of biomass increased by 4–10 times [9]. During the pelletization process, the pelletization temperature and moisture content were the key parameters determining the pelletizability of the sawdust and the hardness of the pellets. Increasing temperature and moisture content generally decreased the energy requirement for pelletization. Increasing temperature yielded stronger pellets, while increasing moisture content might result in weaker pellets because of the lowered wall friction [8].

Self-heating and spontaneous combustion of wood pellets are commonly encountered when large quantities of pellets are stored in silos or containers for extended periods [10]. Pretreatment of the wood may offer solutions to address the biological and thermal degradation of wood pellets. Torrefaction has been practiced as an effective pretreatment for wood preservation and for improving gasification efficiency and controlling tar formation [11–14]. A number of studies have been conducted in recent years, focusing on the torrefaction performance of both forest and agricultural biomass residues [15,16]. Some studies produced torrefied pellets or briquettes from regular pellets or briquettes, leading to poor quality of torrefied pellets/briquettes. Very few studies have been reported in the literature on how to make torrefied sawdust into torrefied pellets, following the same procedures as making regular wood pellets from raw sawdust. In this study, we carried out a systematic study on producing torrefied sawdust from a bubbling fluidized bed reactor and then making the torrefied sawdust into torrefied pellets in a single die compression test unit. The torrefaction performance and properties of torrefied sawdust have been reported in an early paper [17], and the current paper reports the making of torrefied pellets and their properties such as pellet density, moisture uptake and Meyer hardness. The effects of torrefaction severity and compression temperature on the energy consumption and pellet properties were also investigated.

2. Experimental procedure and analysis

2.1. Material

The torrefied samples were prepared in a bubbling fluidized bed reactor as reported in Li et al. [17]. The torrefaction temperature

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and residence time were controlled in the range of 260–300 °C and 10–90 min, respectively. In brief, a weight loss of ~30 wt% was obtained at the following conditions: 260 °C over 30–90 min, 270 °C over 30 min, 280 °C over 15–20 min, 290 °C over 15–20 min, and 300 °C over 10–15 min. In general, the weight loss increased with increasing the torrefaction temperature and/or the residence time. Nitrogen was used as the carrier gas. The properties of the raw samples and two typical torrefied samples are given in Table 1.

2.2. Pelletization and product analysis

A MTI 50 K (Measurement Technology Inc.) press was used for pelletization. A cylinder of 6.35 mm inside diameter and 70 mm in length with a piston 6.30 mm in diameter and 90 mm in length was installed for making a single pellet. The cylinder-piston unit was wrapped by a heating tape with a thermocouple and a temperature controller to preheat the inside cylinder to a certain temperature (also called die temperature). Detailed description of the apparatus and operating procedures can be found in an early publication from our group [18]. In this study, the top hole of the cylinder was filled with approximately 0.5 g sample to make a single pellet of 6.5 mm in diameter and 12 mm in length. The compression rod traveling velocity was 2 mm min^{-1}. The sample was pressed by applying a force of 4000–5000 N and held for 30s. The sample was then further compressed continuously until a maximum force of 6000 N was reached. For making control pellets, i.e. non-torrefied pellets, the die temperature were maintained at 70 °C with 30 s holding time.

According to the preliminary result, torrefied samples were found to be difficult to be formed into strong pellets under the same conditions of making control pellets. Increasing the die temperature has been examined in this study. Some untreated and torrefied pellets were made by increasing the die temperature up to 170 °C with a holding time of 30 s.

In this study, for each sample seven pellets were made and used to determine the properties of pellets. Forces and displacement to form pellets were recorded to calculate the energy consumption. The single pellet density was calculated from measured mass and volume of individual pellet. A humidity chamber (ESPEC CORP, LHU-113, Japan) at 30 °C at 90% relative humidity was used to measure the moisture uptake of torrefied and control pellets [18].

Typical force–displacement curves for compaction and extrusion of sawdust in the MTI machine were shown in Fig. 1a and b, respectively. The energy consumptions associated with compaction and extrusion were obtained by integrating the curve. In the present study, energy consumptions are specifically referred to as the mechanical energy for compaction and extrusion.

Hardness is one of the important characteristics of commercial pellets, which reflects the strength of individual pellet. Forces that cause damage to pellets during handling, transportation, and storage may be divided into compression, impact, and shear forces. In a previous study, several testers were used to measure the hardness of pellets, including the Kahl tester, Stokes tester, Schleuniger tester, tablet hardness tester, universal testing machine (Instron), and Kramer shear strength tester [19]. In the present study, the Meyer hardness against compression from a static indentation test was measured. When a force is applied to the pellet, the pellet will be deformed. The Meyer hardness, H_m, defined as the static indentation hardness, can be determined from the applied force, probe diameter and indentation depth [20].

$$H_m = F/[\pi(Dh - h^2)]$$

where h is the indentation depth; F is the force; and D is the diameter of rod. As defined, the Meyer hardness reflects the resistance of the solid object to various kinds of permanent shape changes when an axial force is applied.

The detail test procedure and the test unit photo were available in our previous report [18].

3. Results and discussion

3.1. Energy consumption

Energy consumptions associated with compression and extrusion of single pellet for untreated and torrefied sawdust are presented in Fig. 2a and b, respectively, as a function of weight loss and torrefaction temperature. Error bars in the figures represent standard deviations of seven replicates. The scattering of data from the seven replicates indicated the heterogeneous nature of sawdust sample and the inconsistency of wood pellets in its mechanical properties, which are consistent with commercial pellet samples with wide ranges of sizes and densities [20,21]. Higher energy input is needed to densify the torrefied sawdust than the untreated sawdust, and the energy requirement increases with increasing the degree of torrefaction or weight loss. During torrefaction, unstable hemicelluloses mainly decomposed while lignin only lost slightly. Therefore, the lignin content in the torrefied sawdust was expected to be higher. If lignin is the main binding agent during pelletization as commonly believed, the torrefied sawdust should be easier to be pelletized. However, our results showed

Table 1
Properties of raw biomass sample and torrefied sawdust (20 wt% and 30 wt% weight loss).

Analysis	Raw sample	Torrefied sample (20 wt% weight loss)[b]	Torrefied sample (30 wt% weight loss)[c]
Chemical composition[a]			
Lignin	51.48	53.39	58.06
Cellulose	27.2	28.76	28.88
Hemicellulose	19.64	14.16	11.88
Elemental composition[a]			
C	48.34	51.29	52.58
H	6.21	5.81	5.66
N	1.50	1.07	1.25
O	43.95	41.83	40.51
Proximate analysis[a]			
Volatile	80.49 ± 2.10		
Fixed Carbon	19.42 ± 2.16		
Ash	0.24 ± 0.02		

[a] Bone dry material, wt%.
[b] 270 °C, 15 min.
[c] 280 °C, 15 min.

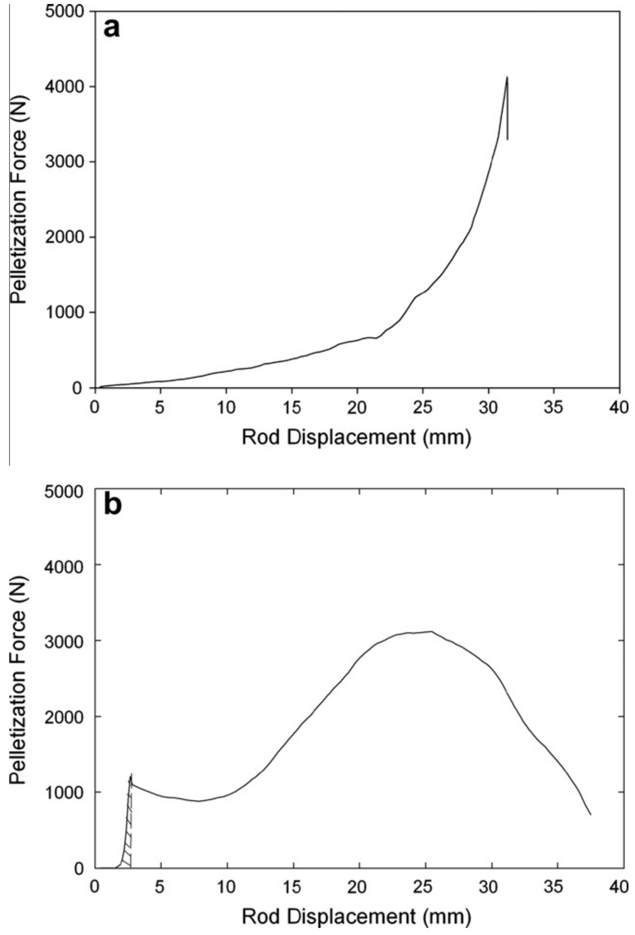

Fig. 1. Typical force vs. displacement graphs. (a) Pellet compression; (b) Pellet extrusion (Shadow area in b is energy consumption for pellet extrusion).

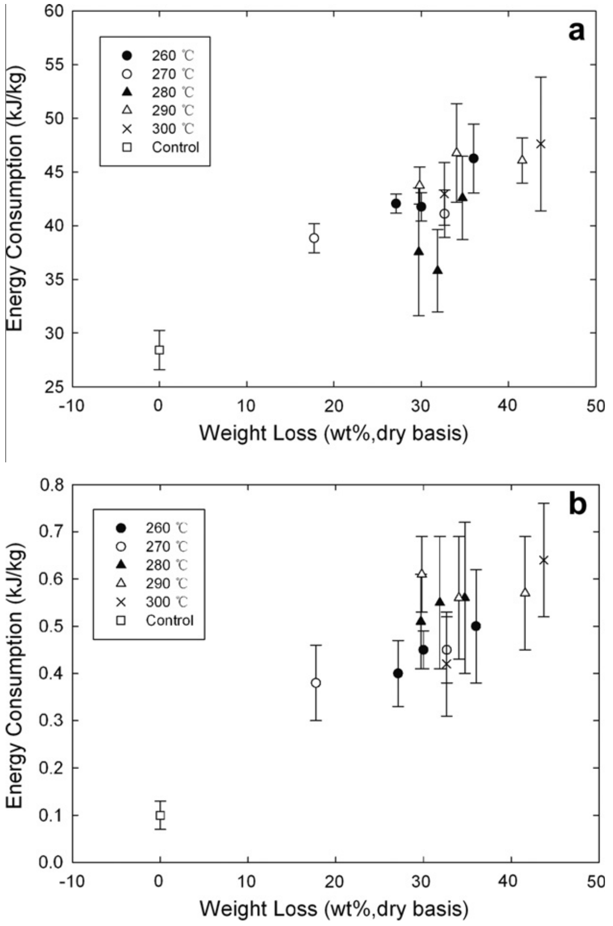

Fig. 2. Energy consumption associated with compression and extrusion as a function of weight loss and torrefaction temperature. Die temperature = 170 °C. (a) Compression of sawdust; (b) Extrusion of pellet.

the opposite trend. This may be due to the removal of most low-melting or low-softening point components during torrefaction. Hydrogen bonding at lignin and hemicellulose surface areas is considered as the main binding in the pelletization process of wood sawdust [22]. The decomposition of hemicelluloses and lignin reduced the plasticity of sawdust, which then contributes to the increased energy consumption during the compression and extrusion. Early study in our group showed that torrefied sawdust could not be pelletized at a die temperature of 100 °C, as commonly used to pelletize untreated sawdust [23]. Higher die temperature is thus needed to make rigid torrefied pellets.

As shown in the previous research of Nielsen et al. [8], the size of particles had a significant effect on the energy consumption for pelletization, which increased with the increase of sawdust size. In the present study using fine torrefied particles from fluidized beds, the higher energy consumption was required for the pelletization of sawdust particles prepared under severe torrefaction conditions, such as 280 °C for 60 min and 300 °C for 60 min. Therefore, for a given particle size, the severity of torrefaction is the primary parameter affecting pelletization because the decomposition of lignin to charcoal, which occurs over a broad temperature range, significantly affected the pelletization [24]. The relaxation of pellets after compression was also observed, indicating that the compression deformation of the fibers was not entirely plastic [8].

The mechanism of particle binding in the absence of adhesives is centered on the function of hydroxyl groups (hydrogen bonding) on the surfaces between particles. During torrefaction, the decomposition of hemicelluloses and lignin reduced the amount of hydroxyl groups. Meanwhile, those intermediate products formed from the decomposition of hemicelluloses and lignin, including acids, sugars and charcoal, were released or coated on the surfaces between wood particles, resulting in a decrease in plasticity. The decrease of particle plasticity increased the energy consumption in the extrusion process, as evidenced from the results in Fig. 2 where the energy consumption in the extrusion process for torrefied pellets was significantly higher than that for control pellets and energy consumption in the extrusion process increased with increasing the weight loss.

Moreover, the standard deviations ($n \geqslant 7$) of energy consumption during pelletization for torrefied sawdust were higher than the control sample. After the torrefaction, the plasticity of particles decreased. The spreading of energy requirement was “magnified” for torrefied sawdust compression.

3.2. Moisture adsorption

Water adsorption by dry torrefied pellets exposed to 90% humidified air at 30 °C in a humidity chamber over 48 h was measured, with the average results shown in Fig. 3. For comparison, the water uptake for untreated pellet control sample was 20.73 wt%. It is seen that the water adsorption capacity of wood decreased significantly after torrefaction. For the torrefied pellet with a 17 wt% weight loss, the water uptake rate dropped to about 13.6 wt%. Further increase in the degree of torrefaction treatment, the water intake of the pellets only decreased moderately to about

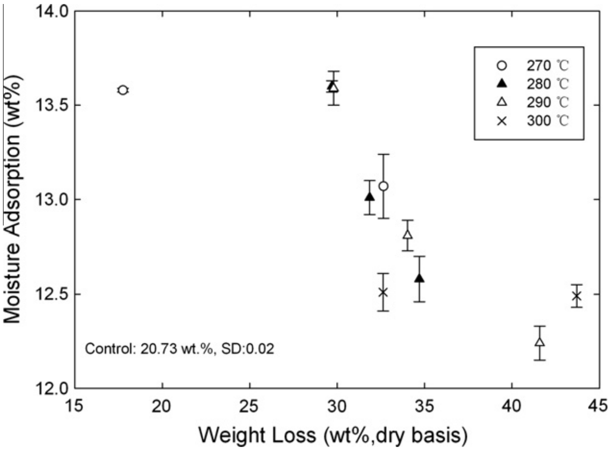

Fig. 3. Effect of weight loss on moisture adsorption of pellets.

12–12.5 wt% at a 40–45 wt% weight loss. Fig. 3 also shows that at the same degree of weight loss, the water uptake rate decreased only slightly with increasing the torrefaction temperature, likely associated with the slight difference in the structure and composition of the torrefied biomass. In two previous studies [22,25], the decomposition of hydroxyl groups and lignin coating on particles were speculated as the two reasons for decreased water uptake rate.

3.3. Pellet density

Pellet density is an important parameter, which determines the energy density per volume and the hardness of the pellets. In this study, the density of single pellet was calculated based on the measured pellet mass and pellet volume with the results shown in Fig. 4. The conditions of torrefaction processes were shown in the previous study [17]. Clear trends could be observed in the figure, in which the density of single pellet made under the same pelleting conditions decreased with increasing the degree of torrefaction. Such a decrease in pellet density is mainly related to the loss of chemically bonded water and low-melting point compounds which act as a binding agent when softened at ~100 °C. To increase the density of torrefied pellets, higher compaction pressure or higher die temperature is required.

3.4. Meyer hardness

The average Meyer hardness was measured for selected pellets, with the average results shown in Fig. 5. The hardness for pellets made at a die temperature of 70 °C from untreated sawdust is about 1.44 N mm^{-2}, which increased to 6.81 N mm^{-2} for untreated pellets made at a die temperature of 170 °C. For torrefied pellets made at a die temperature of 170 °C, it is seen that the hardness was generally lower than the untreated pellets made at the same 170 °C die temperature, but is higher than the hardness of untreated pellets prepared at 70 °C die temperature, a typical temperature for commercial pelleting machines. Also, the hardness of pellets made at the same pelleting condition decreased with increasing the degree of torrefaction, which is consistent with the trend in the pellet density. The low hardness of control pellet made at 70 °C may indicate the existence of pore spaces and gaps in the pellet which reduces the pellet resistance to deformation. This is confirmed from the cross section SEM photo of the untreated pellet (see Fig. 6a), in which clear gaps and spaces were identified in untreated pellets. Lignin of untreated biomass starts to soften at about 70 °C, which acts as a stiffener of the cellulose microfibrils/fibrils and the increased cross linkage of lignin tends to prevent or limit relative movement of particles within the pellet matrix. However, the softened lignin could not flow into structures consisting of hemicelluloses and celluloses, resulting in the internal voids and spaces in the pellet. During the hardness test, the existing gaps and spaces promoted the relative movement of particles within the pellet matrix, leading to the lower hardness for the control pellet made at 70 °C.

Compared with torrefied pellets, control pellets made at 170 °C had a highest hardness of 6.81 N mm^{-2}. The softening of lignin at higher temperatures was considered to be the main reason. When the compression was carried out at 170 °C, lignin inside the sawdust melted, resulting in the improved glass transition. The hardness of pellets was enhanced by increasing the inter-particle contact area or by decreasing the inter-particle distance. From the SEM result, the disappearance of the boundary in the cross section of the control pellet made at 170 °C confirmed that lignin was integrated with other particles after compression.

That the hardness of torrefied pellets was lower than the control pellet made at 170 °C was likely related to the changes in the surface composition as shown in Fig. 6. The decomposition products (for example, charcoal) on the surface of torrefied sawdust particles decreased the hydrogen bonding, resulting in the decrease of particle plasticity.

Among pellets made from the torrefied sawdust with around 30 wt% weight loss, those made at higher torrefaction temperatures and lower residence time could produce pellets of a higher hardness and lower moisture adsorption capacity. In other words,

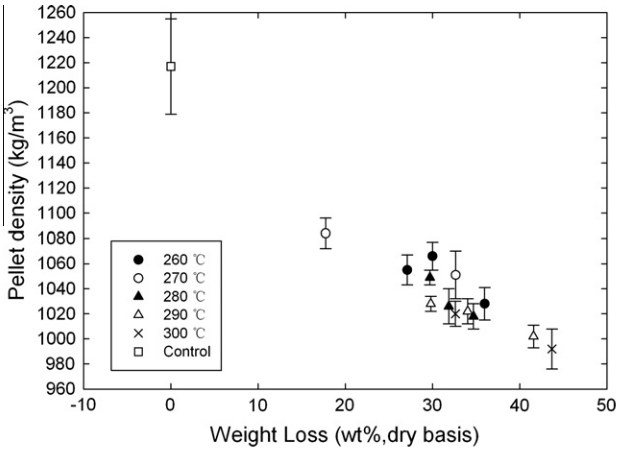

Fig. 4. Density of torrefied pellets as a function of weight loss and torrefaction temperature.

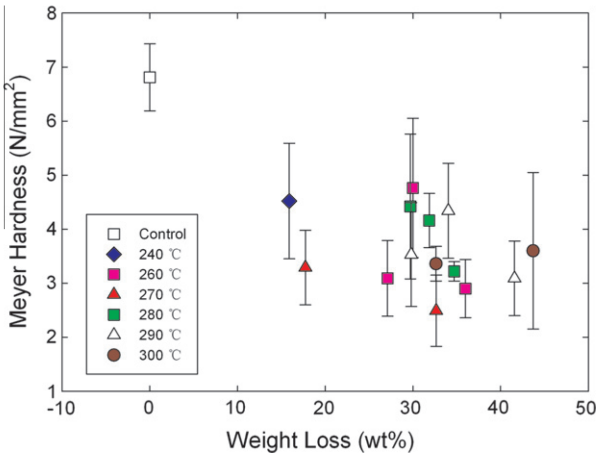

Fig. 5. Meyer hardness of torrefied pellets as a function of torrefaction temperature and residence time.

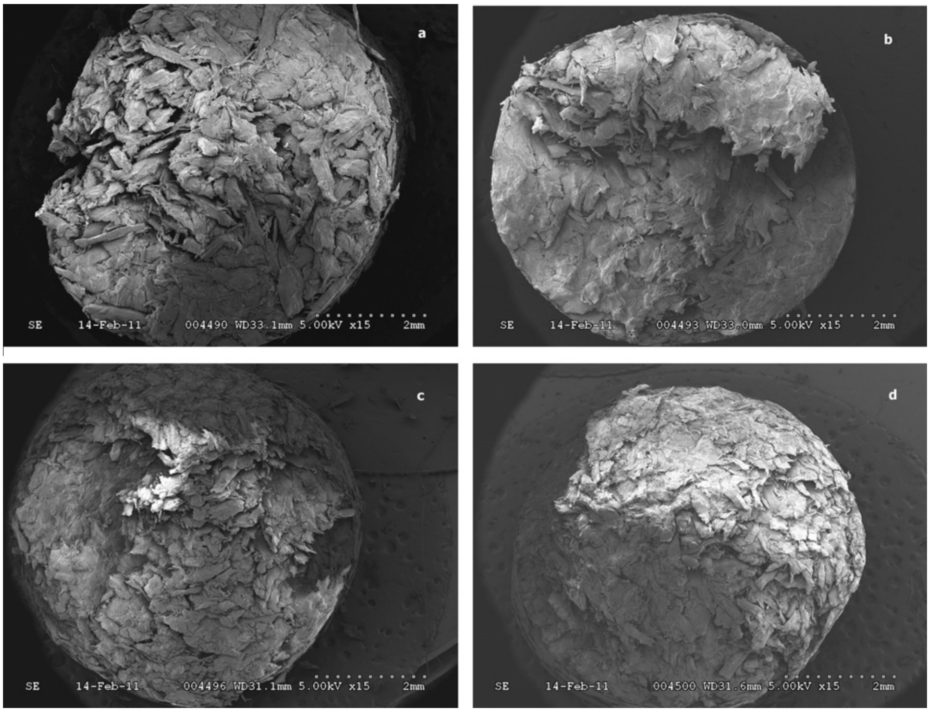
a
SE 14-Feb-11 004490 WD33.1mm 5.00kV x15 2mm
b
SE 14-Feb-11 004493 WD33.0mm 5.00kV x15 2mm
c
SE 14-Feb-11 004496 WD31.1mm 5.00kV x15 2mm
d
SE 14-Feb-11 004500 WD31.6mm 5.00kV x15 2mm

Fig. 6. SEM pictures of untreated and torrefied pellet samples made from sawdust with ~30 wt% weight loss (a) Sawdust pellet made at 70 °C; (b) Sawdust pellet made at 170 °C; (c) Pellet made at 170 °C from torrefied sawdust at 260 °C over 30 min; (d) Pellet made at 170 °C from torrefied sawdust made at 300 °C over 20 min.

a higher reaction temperature and a shorter residence time are preferable conditions for making good quality torrefied pellets.

4. Conclusions

The pelletization process of torrefied sawdust produced from a bubbling fluidized bed was investigated to identify the energy consumption and pellet properties. Energy consumptions for compacting torrefied sawdust into pellets were significantly higher than untreated sawdust at the same compression temperature. The hardness of pellet was reduced in the torrefaction process, while the hardness of pellets decreased with increasing the severity of torrefaction. However, the moisture adsorption of torrefied pellets was lower than pellets from untreated sawdust, while the moisture adsorption of torrefied pellets decreased with increasing the severity of torrefaction.

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